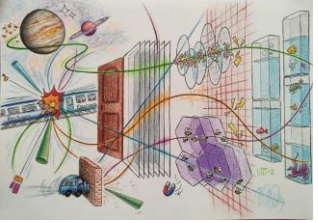
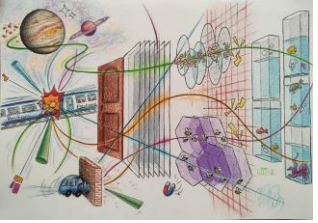


Sensors requirements for the next generation of trackers (excluding monolithic)

N. Cartiglia (INFN Torino), C. Gemme (INFN Genova), A. Macchiolo (University of Zurich)

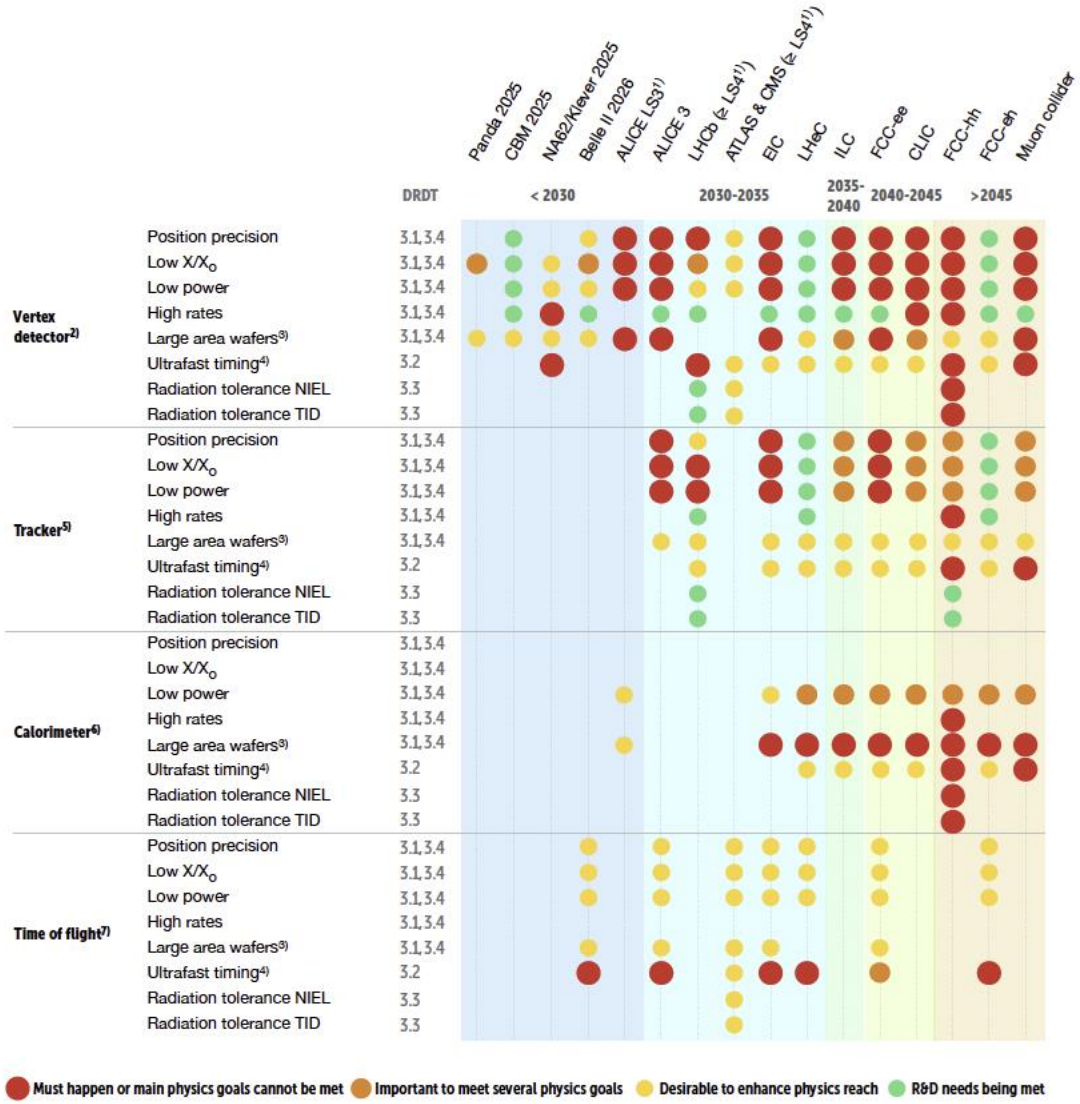
on behalf of the DRD3 proposal writing team



Starting point is ECFA

ECFA has identified solid state sensors with 4D-capabilities one of the pillar for trackers and calorimetry. While the obvious specification are on space and time precision, other parameters are relevant:

- *Material budget, power, rates, occupancy, area and radiation hardness. Moreover interplay with electronics (capacitance, signal shape, etc) has to be considered.*



1) HL-LHC Long shutdowns: LS3/LS4 2025/2031 (see https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm)
2) LHCb/ATLAS/CMS consider Planar/3D sensors at the time of this document for rates and radiation tolerance. On longer term, pixelated LGADs could be considered for potentially higher timing precision.
3) In trackers, coarser longitudinal granularities could be considered for MAPS. Thorough performance and cost comparison with passive CMOS would be needed. Pixelated LGADs could be considered for potentially higher timing precision.
4) The size of wafers achievable can depend on technology (industrial process) with a general trend to benefits from larger areas.
5) Ultrafast timing refers to ≤100 ps depending on technology and detector purpose.
6) Two options exist for calorimetry: pads O(1) mm pitch with analog readout (applying to all technologies) and particle counting digital with MAPS O(50) μm pitch. LGADs could be considered for potentially higher timing precision.
7) ToF, as compared to 4D-tracking, concerns dedicated layers for very high pile-up, beam induced background or particle identification with highest possible precision. Timing erformance of sensors without amplifcation (MAPS, planar/3D/CMOS passive CMOS) is subject to R&D, while LGADs with amplification are at this stage expected to potentially provide higher precision.

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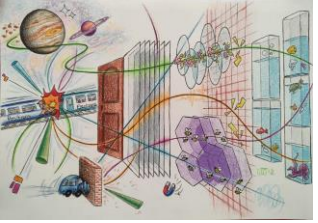


Starting point is ECFA

10.17181/CERN.XDPL.W2EX

DRD3

Of course requirements are significantly different for Vertex, (Outer) Trackers, Space, and Nuclear applications.

In particular, Timing accuracy depends on the application:

- ***Time of Flight (TOF)*** *systems, one or two sensor layers, require the best possible accuracy,*
- ***Large 4D-tracking systems*** *requiring a good track timing identification might have a relatively lower (50-100 ps) single point accuracy requirement, exploiting the capability of multiple measurements*
- *4D-tracking systems that use the temporal information in their* ***pattern recognition sw*** *require a very high single hit timing accuracy,*

"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)				<2030					2030-2035					2035 - 2040	2040-2045		>2045		
				Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3 1)	ALICE 3	LHCb (≥LS4) 1)	ATLAS/CMS (≥ LS4) 1)	EIC	LHeC	ILC 2)	FCC-ee	CLIC 2)	FCC-hh	FCC-eh	Muon Collider
Vertex Detector 3)	MAPS Planar/3D/Passive CMOS LGADs	DRDT3.1 DRDT3.4	Position precision σ_{hit} (μm)		≃ 5		≲ 5	≃ 3	≲ 3	≲ 10	≲ 15	≲ 3	≃ 5	≲ 3	≲ 3	≲ 3	≃ 7	≃ 5	≲ 5
			X/X_0 (%/layer)	≲ 0.1	≃ 0.5	≃ 0.5	≲ 0.1	≃ 0.05	≃ 0.05	≃ 1		≃ 0.05	≲ 0.1	≃ 0.05	≃ 0.05	≲ 0.2	≃ 1	≲ 0.1	≲ 0.2
			Power (mW/cm^2)		≃ 60			≃ 20	≃ 20			≃ 20		≃ 20	≃ 20	≃ 50			
			Rates (GHz/cm^2)		≃ 0.1	≃ 1	≲ 0.1		≲ 0.1	≃ 6		≲ 0.1	≃ 0.1	≃ 0.05	≃ 0.05	≃ 5	≃ 30	≃ 0.1	
			Wafers area (m^2) 4)					12	12			12			12		12		12
		DRDT 3.2	Timing precision σ_t(ns) 5)	10		≲ 0.05	100		25	≲ 0.05	≲ 0.05	25	25	500	25	≃ 5	≲ 0.02	25	≲ 0.02
		DRDT3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)							≃ 6	≃ 2						≃ 10^2		
			Radiation tolerance TID (Grad)							≃ 1	≃ 0.5						≃ 30		
Tracker 6)	MAPS Planar/3D/Passive CMOS LGADs	DRDT3.1 DRDT3.4	Position precision σ_{hit} (μm)						≃ 6	≃ 5		≃ 6	≃ 6	≃ 6	≃ 6	≃ 7	≃ 10	≃ 6	
			X/X_0 (%/layer)						≃ 1	≃ 1		≃ 1	≃ 1	≃ 1	≃ 1	≃ 1	≲ 2	≃ 1	
			Power (mW/cm^2)						≲ 100	≃ 100		≲ 100		≲ 100	≲ 100	≲ 150			
			Rates (GHz/cm^2)							≃ 0.16									
			Wafers area (m^2) 4)						12			12		12	12	12	12		12
		DRDT 3.2	Timing precision σ_t(ns) 5)						25	≲ 25		25	25	≲ 0.1	≲ 0.1	≲ 0.1	≲ 0.02	25	≲ 0.02
		DRDT3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)							≃ 0.3							≲ 1		
			Radiation tolerance TID (Grad)							≃ 0.25							≲ 1		
Calorimeter 7)	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.2	Timing precision σ_t(ns) 5)											≲ 0.05	≲ 0.05	≲ 0.05	≲ 0.02		≲ 0.02
		DRDT 3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)														≳ 10^2		
			Radiation tolerance TID (Grad)														≃ 50		
Time of Flight 8)	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.2	Timing precision σ_t(ns) 5)				≃ 0.02		≃ 0.02		≲ 0.03	≃ 0.02	≃ 0.02		≲ 0.01		≲ 0.01	≃ 0.02	
		DRDT3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)														≃ 10^2		
			Radiation tolerance TID (Grad)														≃ 30		

Values are indicative of performance targets and of operating conditions relevant to R&D. The latter are reported for the regions most exposed to radiation. Empty cells indicate either that projects are not concerned; or that specifications are already met or not yet fully established, for instance power consumption depends strongly on granularity and digital features that would be finally implemented.

1) LS3/LS4 are scheduled to start in 2025/2031 at the time of this document.

2) Reported rates are within the bunch trains.

3) LHCb/ATLAS/CMS consider Planar/3D sensors at the time of this document for rates and radiation tolerance. Pixelated LGADs could already be considered for NA62/Klever andfor longer term Vertex Detectors for timing precision for high timing precision.

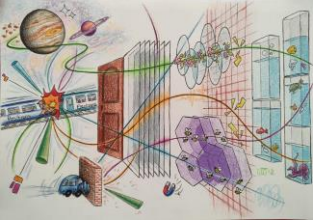
4) The size of wafers achievable can depend on technology (industrial process) with a general trend to benefits from larger areas.

5) Ultrafast timing ≲ 100 ps could be differently achieved by the various technologies.

6) In trackers, coarser longitudinal granularities could be considered for MAPSs. Thorough performance and cost comparison with Passive CMOS would be needed. Pixelated LGADs could be considered for potentially higher timing precision.

7) Two options exist for calorimetry: pads O(1) mm pitch with analog readout (applying to all technologies) and particle counting digital with MAPSs O(50) μm. LGADs could be considered for potentially higher timing precision. DRT 3.1 apply w/o the X/X_0 constraint. DRT 3.4 could achieve higher compactness and be needed for the digital options to integrate full readout within the sensor area.

8) TOF, as compared to 4D-tracking, concerns dedicated layers for very high pile-up, beam induced background or particle identification with highest possible precision. Timing performance of sensors w/o amplifcation (MAPS, planar/3D/CMOS passive CMOS) is subject to R&D, while LGADs w/ amplification are at this stage expected to potentially provide higher precision. DRT 3.1 and DRT 3.4 of Vertex Detector and Tracker apply with less stringent requirement.

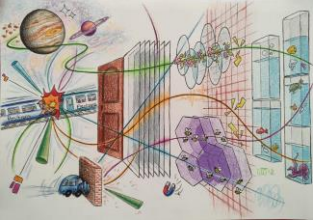


Detectors needs

DRD3

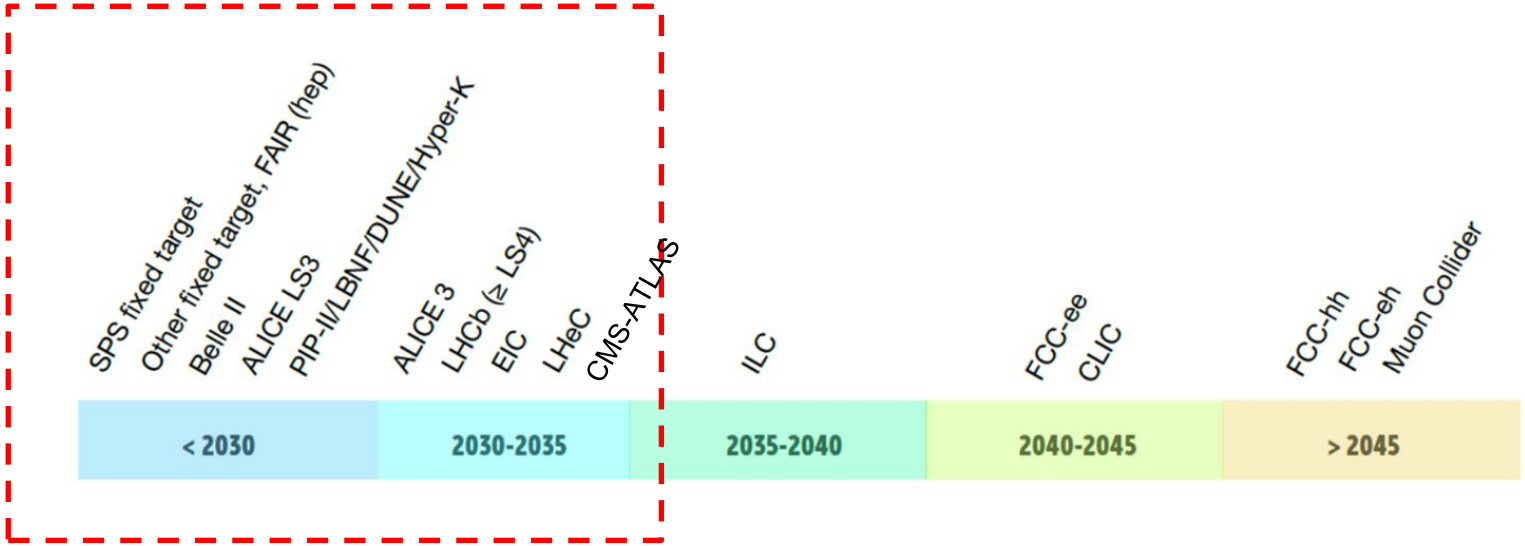
In WP2, the strategy is to develop technologies that may be adopted by the experiments when the time comes: in the next slides, <u>examples</u> of needs are summarized.

- There are commonalities in the possible SSD technological choices since both **hadrons and e^+e^- colliders** require low mass, low power, and high-resolution trackers.
- Nonetheless, **hadron colliders** necessitate ultra-fast detectors, enabling 4D-tracking to deal with multiple interactions occurring within a bunch crossing (pile-up). Detectors at FCC-hh must also achieve unprecedented radiation hardness.



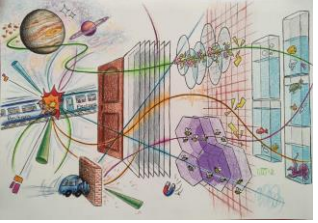
Timeline

DRD3



In the next few slides, the needs of this group of experiments are outlined.

Disclaimer: the list may be incomplete, other experiments may have similar requirements.

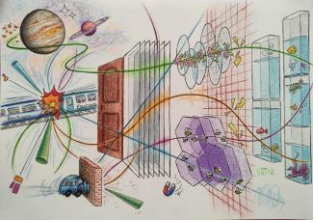


ATLAS/CMS@HL-LHC

DRD3

ATLAS/CMS are planning to install completely new detectors in LS3 (2026-28). As described in the TDRs, vertex detectors are planning *partial* replacement at ~ half lifetime.

- The replacement involves the areas more exposed to large fluences and doses**.**
- Similar requirements as the current systems, but of course improvements in terms of pixel size, material budget and timing will be welcome.
- It will represent an Intermediate step for future hadrons colliders, FCC-hh …

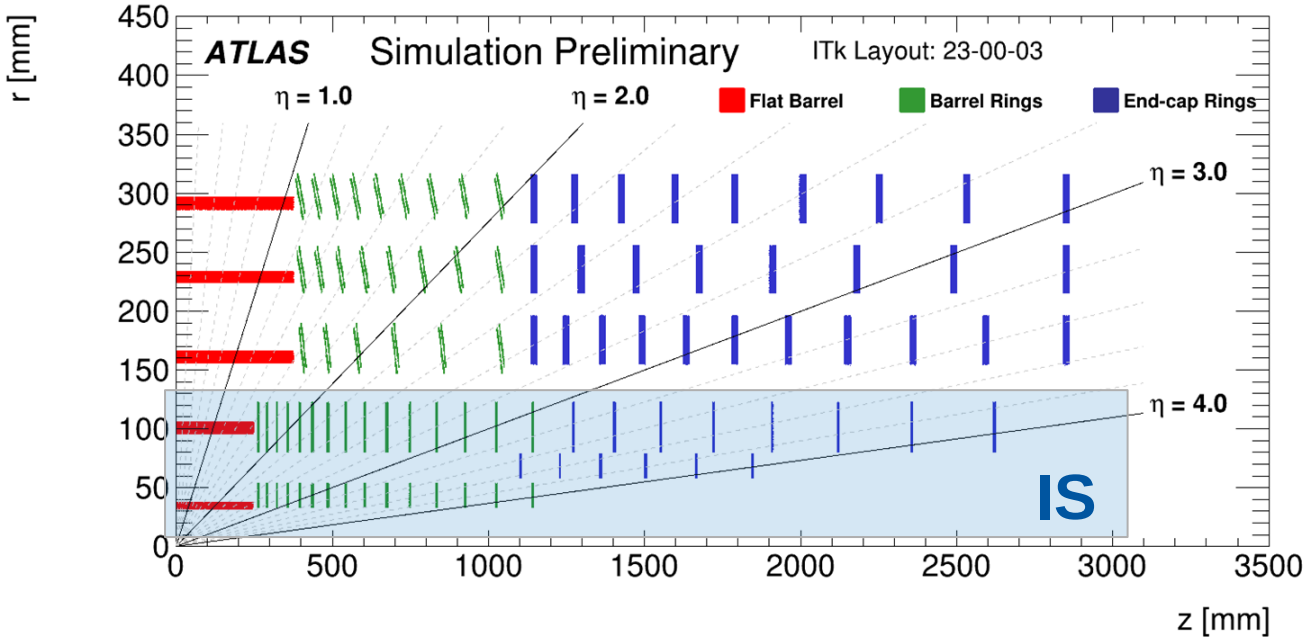


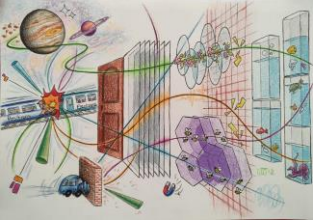
ATLAS@HL-LHC

DRD3

ATLAS is planning to replace the full Inner System after about half lifetime, ~2000 ifb (LS5?).

- Currently done by L0 in 3D (25x100 um^2 in the barrel and 50x50 um^2 in the EC, at 34/33 mm from the IP respectively) and 100um planar sensors in L1.
- A pretty large detector ~2.4 m^2 (Larger than the current Run3 ATLAS pixel detector)



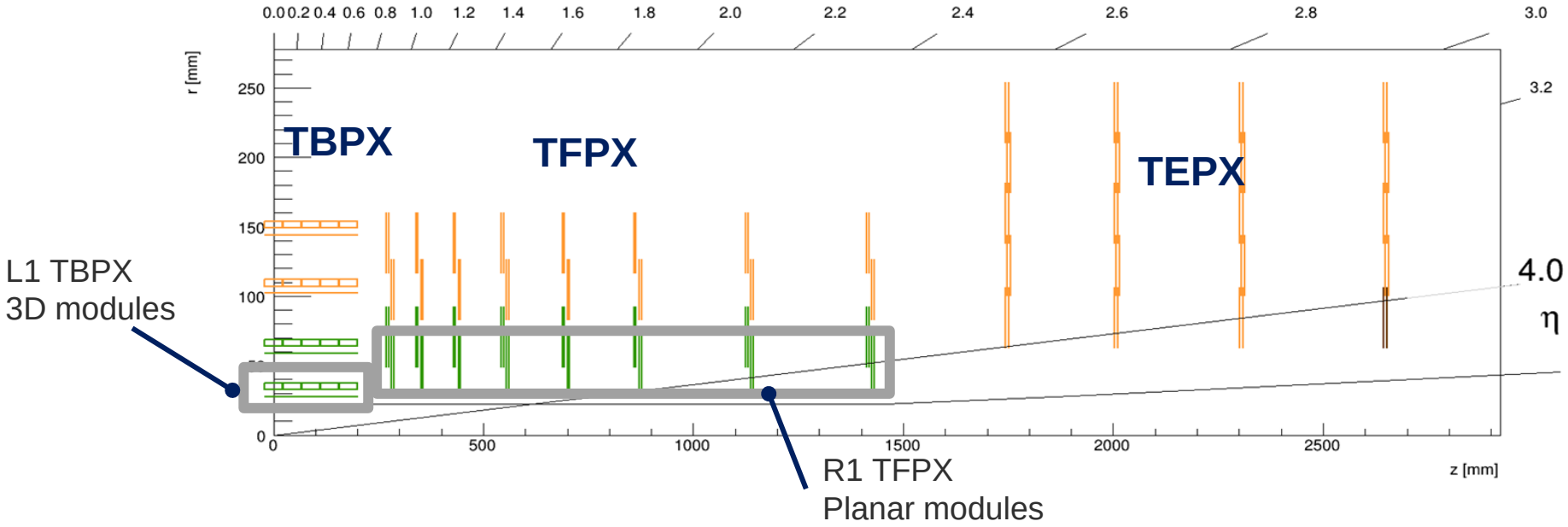


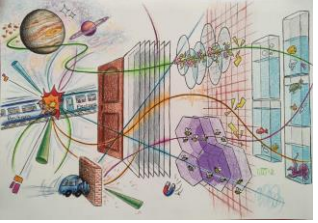
CMS@HL-LHC

DRD3

CMS is also planning to replace part of the detector. Similar concept of accessibility as today, thus allowing more access to damaged parts.

- Plan to replace L1 TBPX 3D modules and R1 TFPX R1 planar modules, Area is ~ 0.4 m^2.



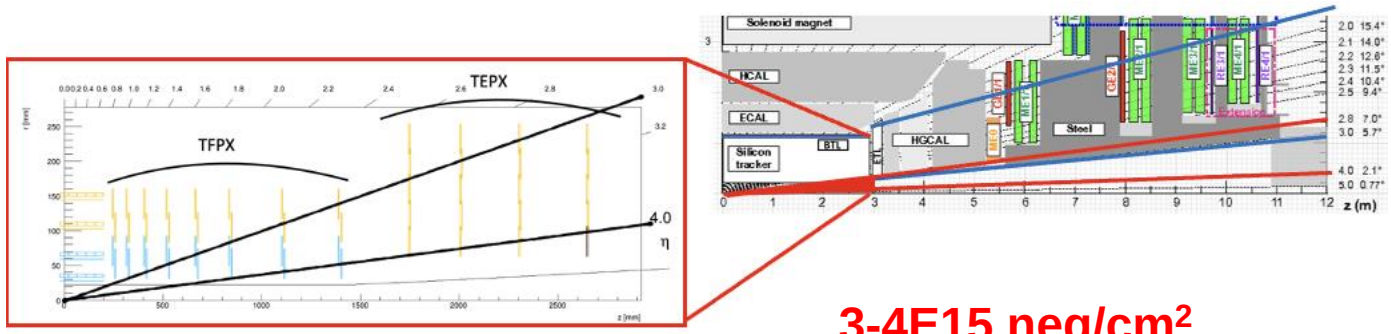


CMS@HL-LHC

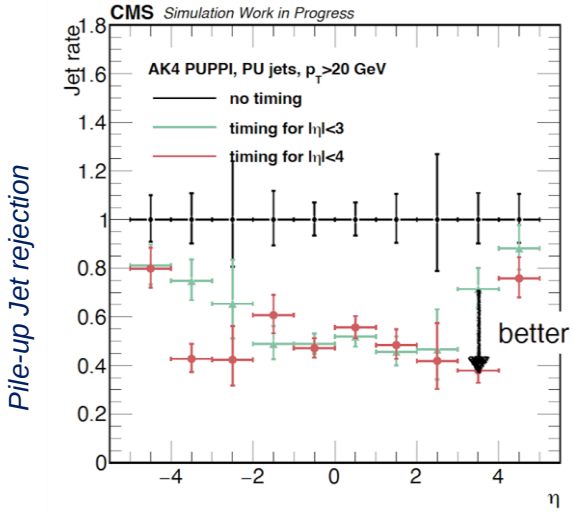
DRD3

CMS is also planning to replace part of the detector. Similar concept of accessibility as today, thus allowing more access to damaged parts.

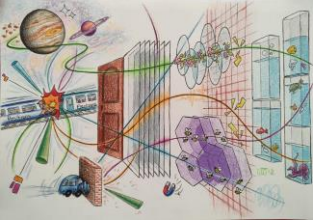
- Plan to replace L1 TBPX 3D modules and R1 TFPX R1 planar modules, Area is ~ 0.4 m^2.
- **Done studies to improve timing resolution in the very forward region for pile-up rejection, also as an intermediate step (LS4?)**
  - ETL covering a region from 1.6 < |η| < 3.0. Replacing one/two disks or adding one disks in TEPX could extending timing up to |η| < 4



3-4E15 neq/cm²



A. Albrecht, DPG Conference, March 2022



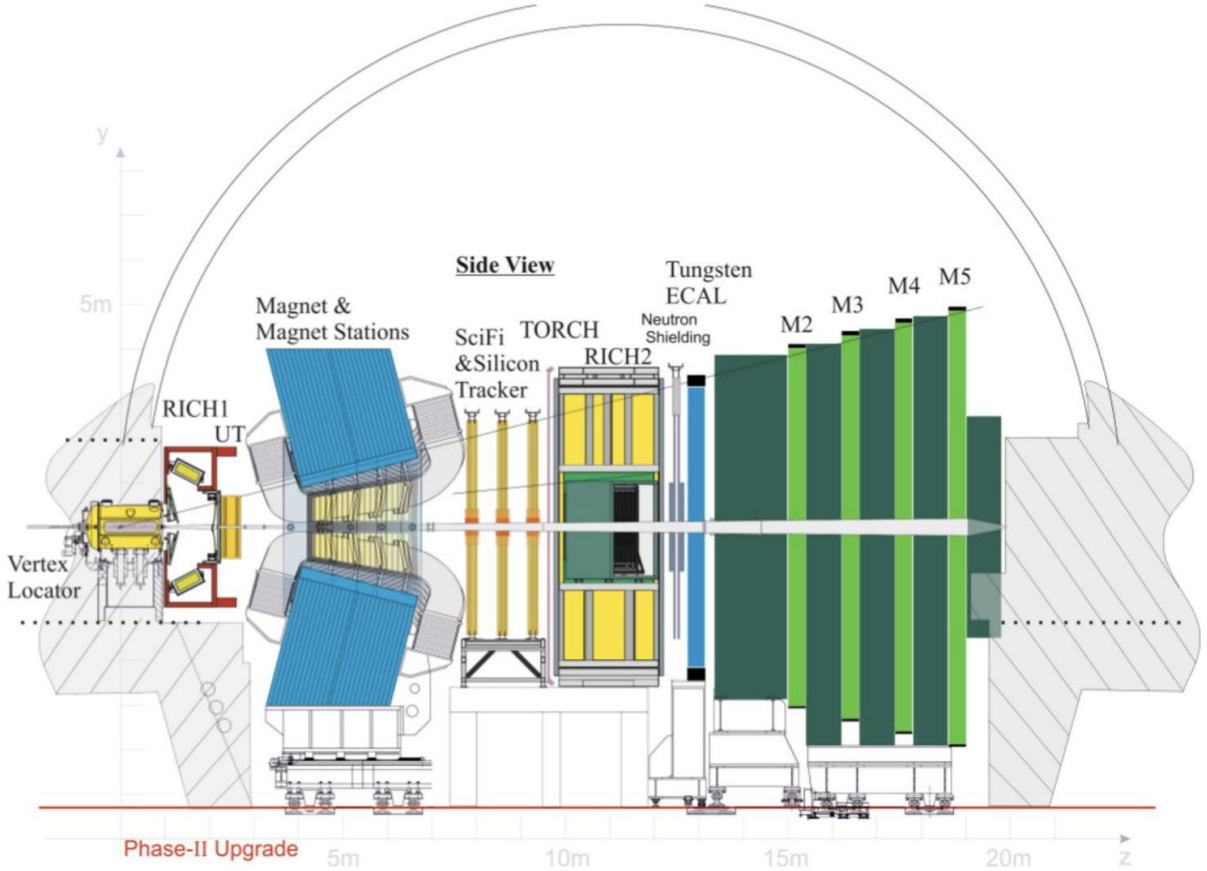
LHCb@HL-LHC

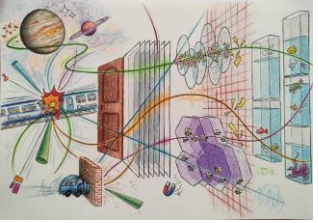
DRD3

Details in LHCb-PUB-2022-001
LHCB-TDR-023

LHCb Upgrade2 in LS4 (2033-34)

- The tracking system will consist of a Vertex Locator (**VELO**) and tracking stations placed upstream (**Upstream Tracker, UT**) and downstream the magnet (**Mighty Tracker, MT**). The Mighty Tracker will be split in an Silicon Tracker covering the inner region, and a Scintillating Fiber Tracker (SciFi) covering the outer region.
- **Focus on Velo**.





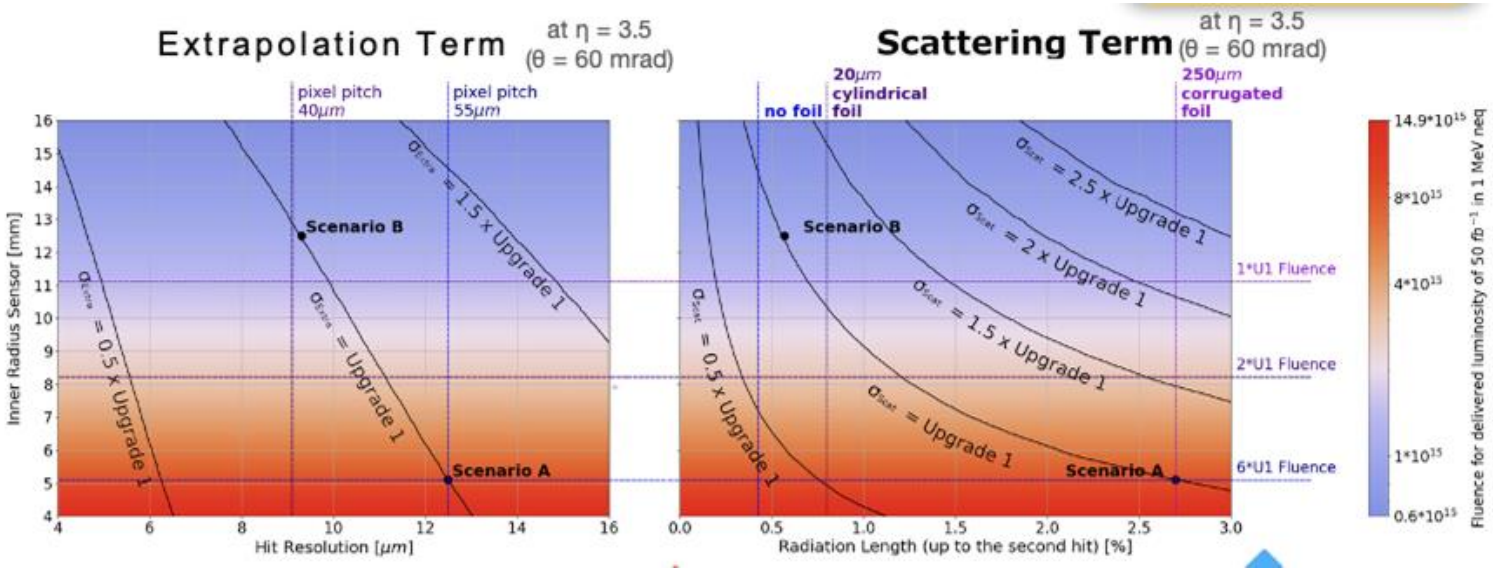
LHCb@HL-LHC

DRD3

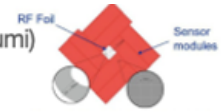
Details in LHCb-PUB-2022-001
LHCB-TDR-023

LHCb Upgrade2 in LS4

- A new VELO installed in LS2 in 2022. Pixel detector at 5.1 mm from the IP, 55x55 um2, 400 MRad tolerance.
- Two scenarios at different radius/pitch used to target R&D for LS4 upgrade for operation at inst. luminosity x 7.5 wrt Upgrade1.



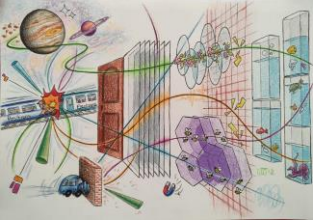
Scenario A (SA) (same as in UI, at 7.5× lumi)



- 5.1 mm inner radius
- 55 × 55 μm pixels
- 6 × 10^{16} 1 MeV n_{eq} cm^{-2} maximum fluence, 3 Grad ionising dose
  - highly non homogeneous
  - radiation harder sensors or regular replacement
- >250 Gb/s ASIC bandwith (900 Mtracks/cm^2/s)

Scenario B (SB)

- 12.5 mm inner radius
- 42 × 42 μm pixels
- 5× reduction of material budget before 2nd hit
  - much thinner RF foil or substitution with wires
- 8 × 10^{15} 1 MeV n_{eq} cm^{-2} maximum fluence, 400 Mrad ionising dose
- >94 Gb/s ASIC bandwith



LHCb@HL-LHC

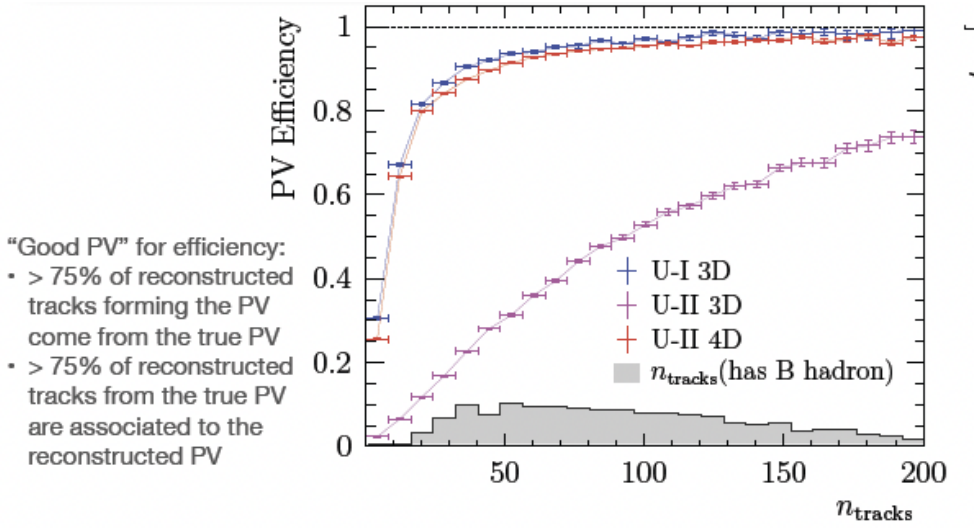
DRD3

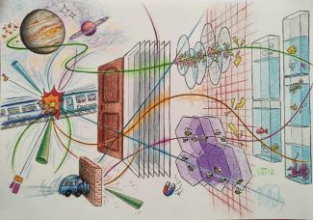
Details in LHCb-PUB-2022-001
LHCB-TDR-023

LHCb Upgrade2 in LS4

- A new VELO installed in LS2 in 2022. Pixel detector at 5.1 mm from the IP, 55x55 um2, 400 MRad tolerance.
- Two scenarios at different radius/pitch used to target R&D for LS4 upgrade for operation at inst. luminosity x 7.5 wrt Upgrade1. It is required:
  - **50 ps per-hit** resolution
  - plus (at least) one of the following
    - **radiation tolerance to 6 × 10^{16} 1 MeV n_{eq} cm^{-2}** (or regular replacement of some modules); ability to deal with extreme rates (**350 kHz/pixel**, **250 Gb/s per ASIC**)
    - **80% X_0 reduction before 2nd hit** (implies **operation in the LHC vacuum**) and **9 µm hit resolution**

20 ps for track (50 ps per hit) restore U-1 performance





Alice@HL-LHC

DRD3

Alice 3 LoI CERN-LHCC02022-009

Alice 3 in LS4 (2033-34)

- High readout rate, superb pointing resolution and excellent tracking and particle identification over a large acceptance.
  - **Vertex**: the first tracking layer must be placed as close as possible to the interaction point. Detector must be retractable.
  - A large active area **Outer Tracker** with barrel and endcap layers over a large acceptance by measuring about 10 space points.
  - For **PID**, a time-of-flight detector and a ring-imaging Cherenkov detector, both relying on novel silicon timing and photon sensors.
- **Focus on ToF.**

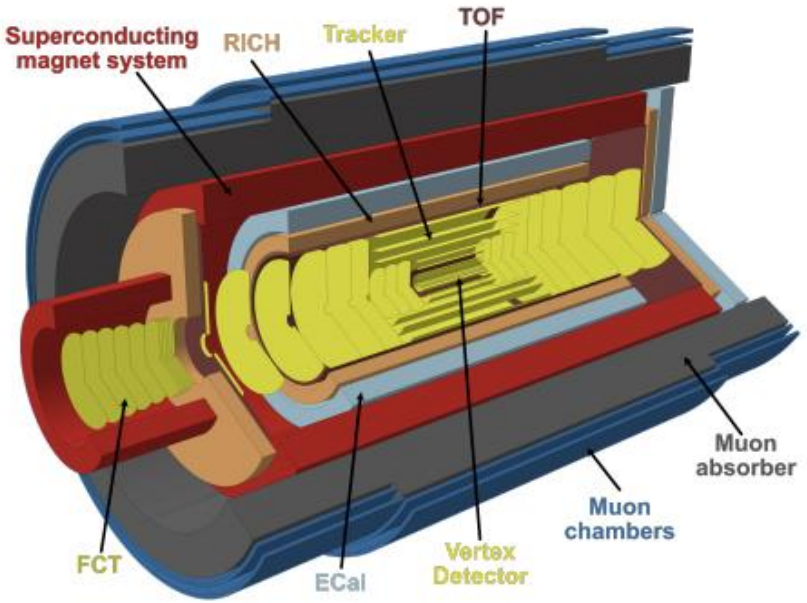
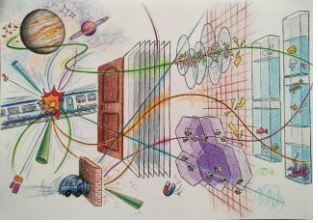


Figure 1: ALICE 3 detector concept: A silicon tracker composed of cylinders and disks serves for track reconstruction in the magnetic field provided by a super-conducting magnet system. The vertex tracker is contained within the beam pipe. For particle identification a time-of-flight detector, RICH detector, photon detector, and a muon system are employed. The forward conversion tracker is housed in a dedicated dipole magnet.



Alice@HL-LHC

DRD3

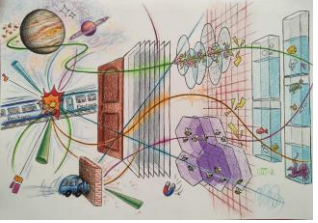
Alice 3 LoI CERN-LHCC02022-009

Alice 3 ToF in LS4 (2033-34)

- A time resolution of 20 ps r.m.s. together with low material budget of 1-3%X0 and a power density of 50 mW/cm2 are the key requirements.
- ALICE ToF is an ideal candidate to **scale to large areas** current 4D silicon sensors R&Ds, as Large area systems as needed for ALICE 3 have not yet been built.
  - Three sensor technologies have been identified as candidates for dedicated R&D in the coming years: fully depleted CMOS sensors, Low-Gain Avalanche Diodes (LGAD) and Single Photon Avalanche Diodes (SPAD).

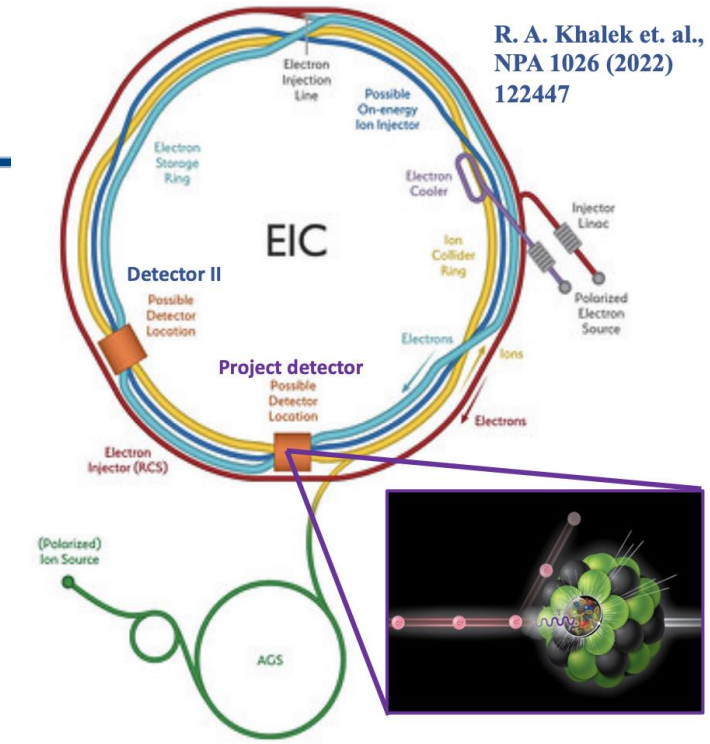
	Inner TOF	Outer TOF	Forward TOF
Radius (m)	0.19	0.85	0.15–1.5
z range (m)	–0.62–0.62	–2.79–2.79	4.05
Surface (m^2)	1.5	30	14
Granularity (mm^2)	1×1	5×5	1×1 to 5×5
Hit rate (kHz/cm^2)	74	4	122
NIEL (1 MeV n_{eq}/cm^2) / month	1.3×10^{11}	6.2×10^{9}	2.1×10^{11}
TID (rad) / month	4×10^{3}	2×10^{2}	6.6×10^{3}
Material budget ($\%X_0$)	1–3	1–3	1–3
Power density (mW/cm^2)	50	50	50
Time resolution (ps)	20	20	20

Table 11: TOF specifications.



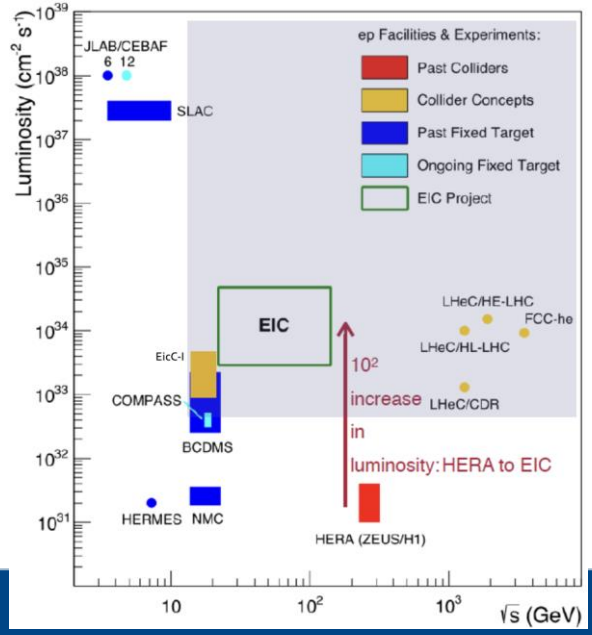
EPIC detector@EIC

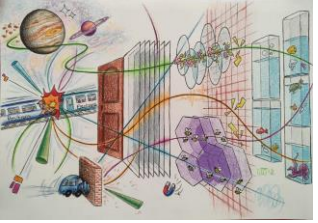
R. A. Khalek et. al., NPA 1026 (2022) 122447



The Electron-Ion Collider project has received CD1 approval from the US DOE in 2021 and will be built at BNL.

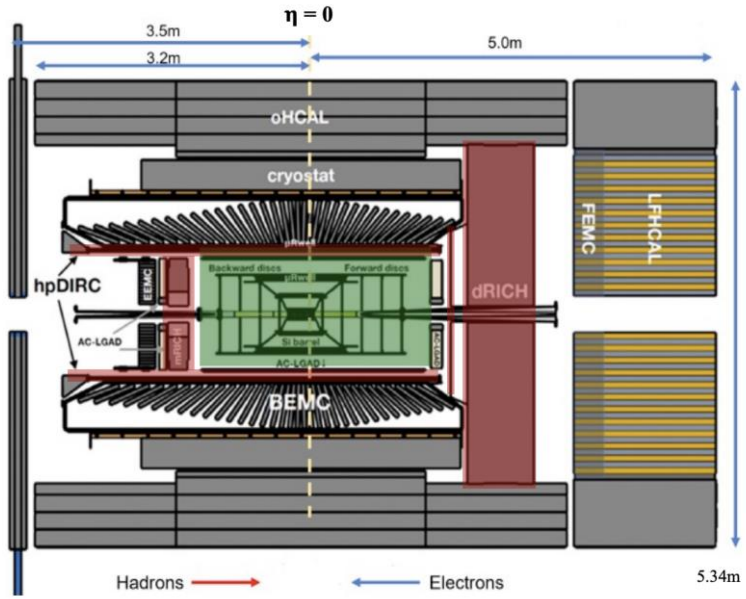
- The EPIC detector design consists of optimized tracking, PID and calorimeter subsystems.
- Planning **for 4D in 3+1 approach,** with precise thin spatial planes and additional layer dedicated to timing, thus decoupling the requirements on the detector technology.



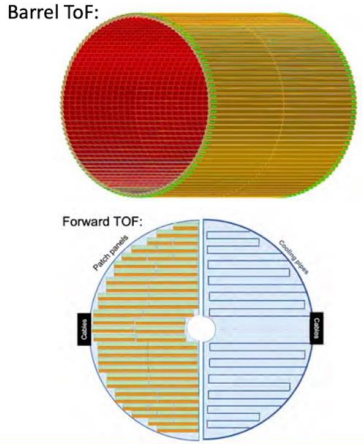


EPIC detector@EIC

DRD3

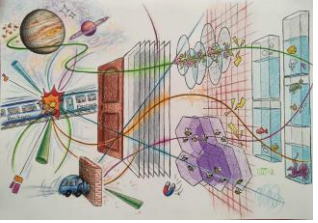


The high granularity and low material budget EPIC vertex and tracking detector in the barrel, hadron endcap and electron endcap regions. Timing layer/plane (AC coupled Low Gain Avalanche Diode, AC-LGAD) serves as the outer tracker in the barrel/ hadron Endcap.



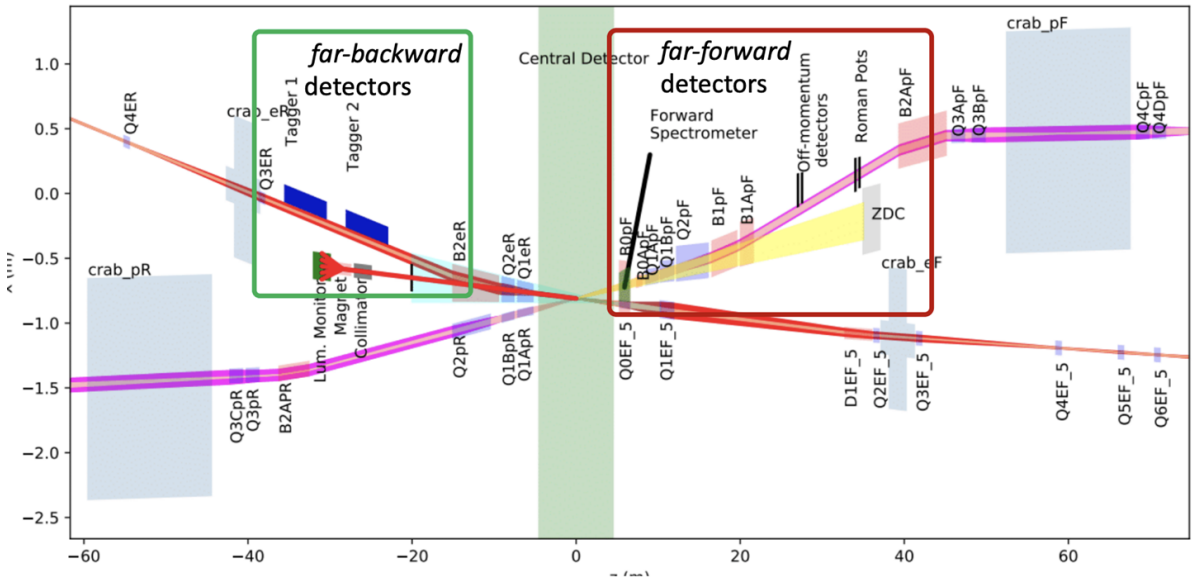
- Barrel AC-LGAD tracker (ToF):
  - Pixel size 0.5mm by 1.0mm.
  - 10.9 m^2 active area with 2.4M channels.
  - Spatial resolution 30 μm in $r\varphi$.
  - Timing resolution 30 ps.
- Hadron endcap AC-LGAD tracker (ToF):
  - Pixel size 0.5mm by 0.5mm.
  - 2.22 m^2 active area with 8.8M channels.
  - Spatial resolution 30 μm in xy.
  - Timing resolution 25 ps.

Detailed detector geometry of the barrel and hadron endcap AC-LGAD tracker (ToF) has been developed.



EPIC detector@EIC

DRD3

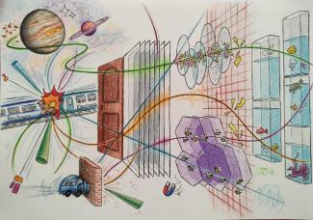


- Central detector spans 9 meters and is machine-component free (except for beam pipe).
- Hadron-going and electron-going directions after central detector fully instrumented.
- Hadron and electron beam cross with an angle of 25 mrad.

Additionally, Roman Pots also have similar requirements:

- Fast timing (~35ps) to remove vertex smearing effect from crab rotation.
- 500um x 500um pixels.
- Radiation hardness (although not as stringent as LHC).
- Large active area (25cm x 10cm).

Finally, the position of LGAD in the calorimeter is considered.



Belle-2

DRD3

The Belle II Detector Upgrade Program

Belle is planning an upgrade for high luminosity

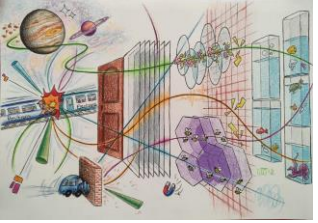
- Medium term ~ 2026-27: A new Vertex Detector might be required to accommodate the new IR design

Long term beyond 2032:

- Studies have started to explore upgrades beyond the currently planned program, such as beam polarization and ultra-high luminosity, possibly L_{peak} in excess of 1×10^{36} cm^{-2} s^{-1}. While the beam polarization has a concrete proposal, for ultra-high luminosity studies have just started.

Subdector	Function	upgrade idea	time scale
PXD	Vertex Detector	2 layer installation	short-term
		new DEPFET	medium-term
SVD	Vertex Detector	thin, double-sided strips, w/ new frontend	medium-term
PXD+SVD	Vertex Detector	all-pixels: SOI sensors	medium-term
		all-pixels: DMAPS CMOS sensors	medium-term
CDC	Tracking	upgrade front end electronics	short/medium-term
		replace inner part with silicon	medium/long term
		replace with TPC w/ MPGD readout	long-term
TOP	PID, barrel	Replace conventional MCP-PMTs	short-term
		Replace not-life-extended ALD MCP-PMTs	medium-term
		STOPGAP TOF and timing detector	long-term
ARICH	PID, forward	replace HAPD with Silicon PhotoMultipliers	long-term
		replace HAPD with Large Area Picosecond Photodetectors	long-term
ECL	γ, e ID	add pre-shower detector in front of ECL	long-term
		Replace ECL PiN diodes with APDs	long-term
		Replace CsI(Tl) with pure CsI crystals	long-term
KLM	K_L, μ ID	replace 13 barrel layers of legacy RPCs with scintillators	medium/long-term
		on-detector upgraded scintillator readout	medium/long-term
		timing upgrade for K-long momentum measurement	medium/long-term
Trigger		firmware improvements	continuos
DAQ		PCIe40 readout upgrade	ongoing
		add 1300-1900 cores to HLT	short/medium-term

Spare



LHC timeline

DRD3

LHC and HL-LHC luminosity and irradiation profiles for Radiation Protection studies
EDMS Document Number: 2641646

Table 4: Integrated luminosities per calendar year and peak luminosities used for the calculation of collision profiles (proton-proton) for Point 8 (LHCb).

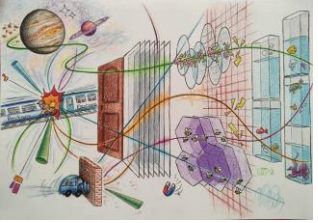
Run	Year	Integrated luminosity per year [fb^{-1}]	Levelled luminosity [$cm^{-2}\,s^{-1}$]
Run 3	2022	7.5	2.0×10^{33}
	2023	7.5	2.0×10^{33}
	2024	7.5	2.0×10^{33}
	2025	7.5	2.0×10^{33}
Long Shutdown 3			
Run 4	2029	1.90	2.0×10^{33}
	2030	7.61	2.0×10^{33}
	2031	8.97	2.0×10^{33}
	2032	10.44	2.0×10^{33}
Long Shutdown 4			
Run 5	2034	11.1	2.0×10^{33}
	2035	11.6	2.0×10^{33}
	2036	11.6	2.0×10^{33}
Long Shutdown 5			
Run 6	2038	12.77	2.0×10^{33}
	2039	12.77	2.0×10^{33}
	2040	12.77	2.0×10^{33}
	2041	12.77	2.0×10^{33}
	2042	12.77	2.0×10^{33}

Table 3: Integrated luminosities per calendar year and peak luminosities used for the calculation of Run 5 and Run 6 collision profiles (proton-proton) for Point 2 (ALICE).

Run	Year	Integrated luminosity per year [fb^{-1}]	Levelled luminosity [$cm^{-2}\,s^{-1}$]
Run 5	2034	0.0776	2.0×10^{31}
	2035	0.0812	2.0×10^{31}
	2036	0.0812	2.0×10^{31}
Long Shutdown 5			
Run 6	2038	0.0772	2.0×10^{31}
	2039	0.0894	2.0×10^{31}
	2040	0.0894	2.0×10^{31}
	2041	0.0894	2.0×10^{31}
	2042	0.0894	2.0×10^{31}

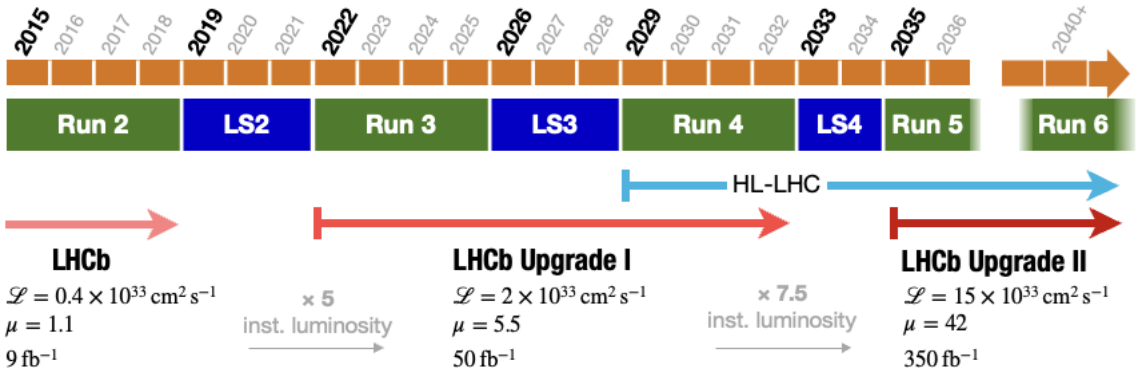
Table 1: Integrated luminosities per calendar year and peak luminosities used for the calculation of Run 3, Run 4 and HL-LHC collision profiles (proton-proton) for Point 1 (ATLAS) and Point 5 (CMS).

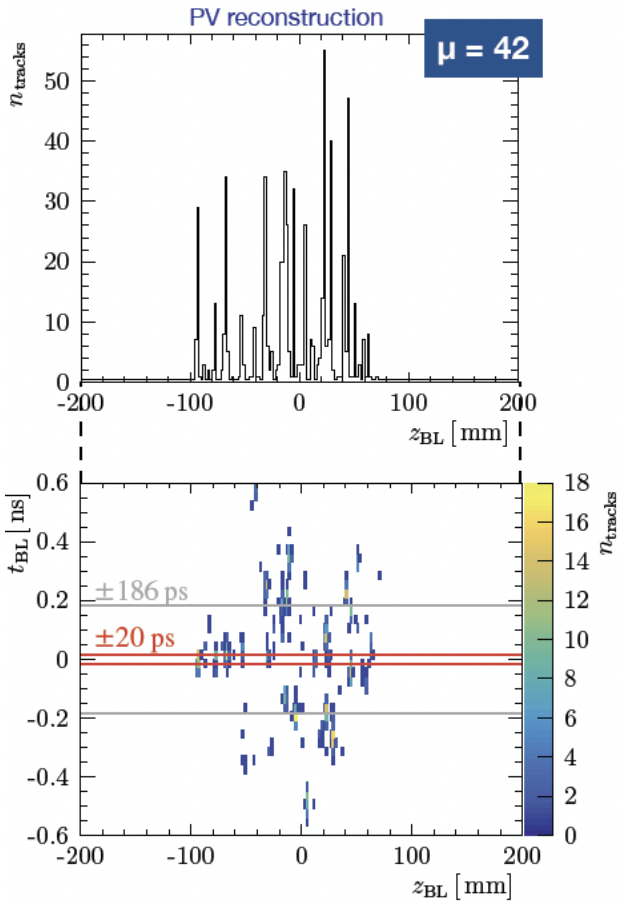
Run	Year	Integrated luminosity per year [fb^{-1}]	Levelled luminosity [$cm^{-2}\,s^{-1}$]
Run 3	2022	35	2.0×10^{34}
	2023	90	2.0×10^{34}
	2024	90	2.0×10^{34}
	2025	90	2.0×10^{34}
Long Shutdown 3			
Run 4	2029	18.5	4.0×10^{34}
	2030	73.8	4.0×10^{34}
	2031	215	5.0×10^{34}
	2032	254	5.0×10^{34}
Long Shutdown 4			
Run 5	2034	270	5.0×10^{34}
	2035	405	7.5×10^{34}
	2036	405	7.5×10^{34}
Long Shutdown 5			
Run 6	2038	385	7.5×10^{34}
	2039	445	7.5×10^{34}
	2040	445	7.5×10^{34}
	2041	445	7.5×10^{34}
	2042	445	7.5×10^{34}



LHCb

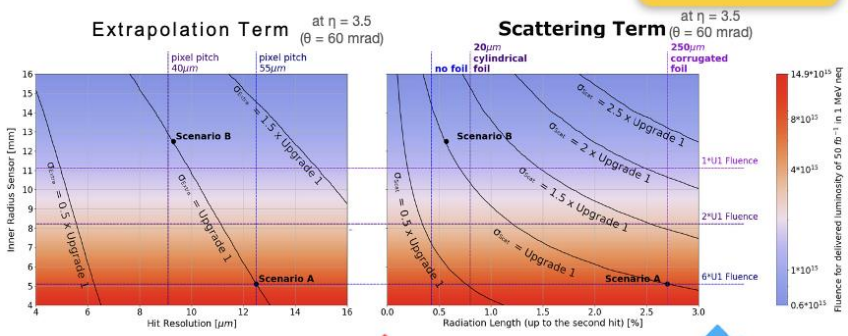
DRD3





How far from the beam?

$$\sigma_{\mathrm{IP}} = \sigma_{\mathrm{extra}} \oplus \frac{\sigma_{\mathrm{scat}}}{p_{\mathrm{T}}}$$



Scenario A (SA) (same as in UI, at 7.5× lumi)

- 5.1 mm inner radius
- 55 × 55 μm pixels
- 6 × 10^{16} 1 MeV n_{eq} cm^{-2} maximum fluence, 3 Grad ionising dose
  - highly non homogeneous
  - radiation harder sensors or regular replacement
- >250 Gb/s ASIC bandwith (900 Mtracks/cm²/s)

Scenario B (SB)

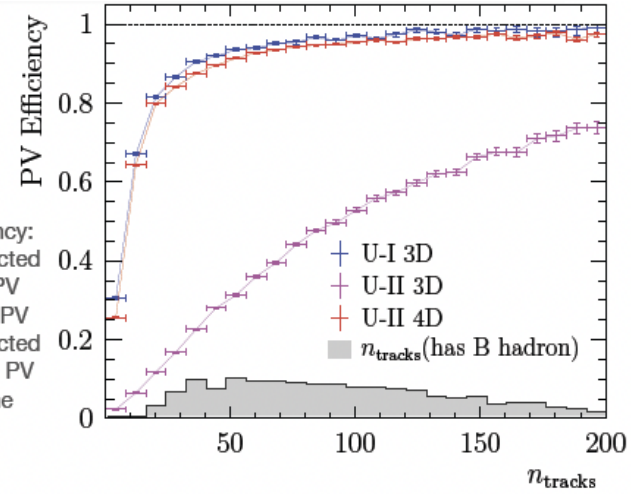
- 12.5 mm inner radius
- 42 × 42 μm pixels
- 5× reduction of material budget before 2nd hit
  - much thinner RF foil or substitution with wires
- 8 × 10^{15} 1 MeV n_{eq} cm^{-2} maximum fluence, 400 Mrad ionising dose
- >94 Gb/s ASIC bandwith

12 Dec 2022 T. Pajero | Pixel 2022: The LHCb 4D pixel detector 4

20 ps for track (50 ps per hit) restore U1 performance

"Good PV" for efficiency:

- > 75% of reconstructed tracks forming the PV come from the true PV
- > 75% of reconstructed tracks from the true PV are associated to the reconstructed PV

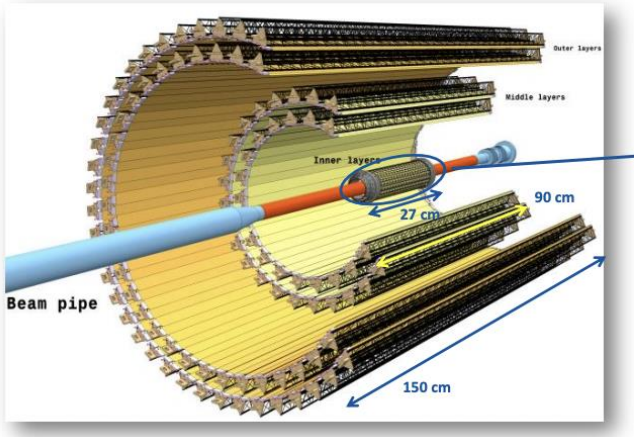


Alice@HL-LHC from Ph-1 to Ph-2/3

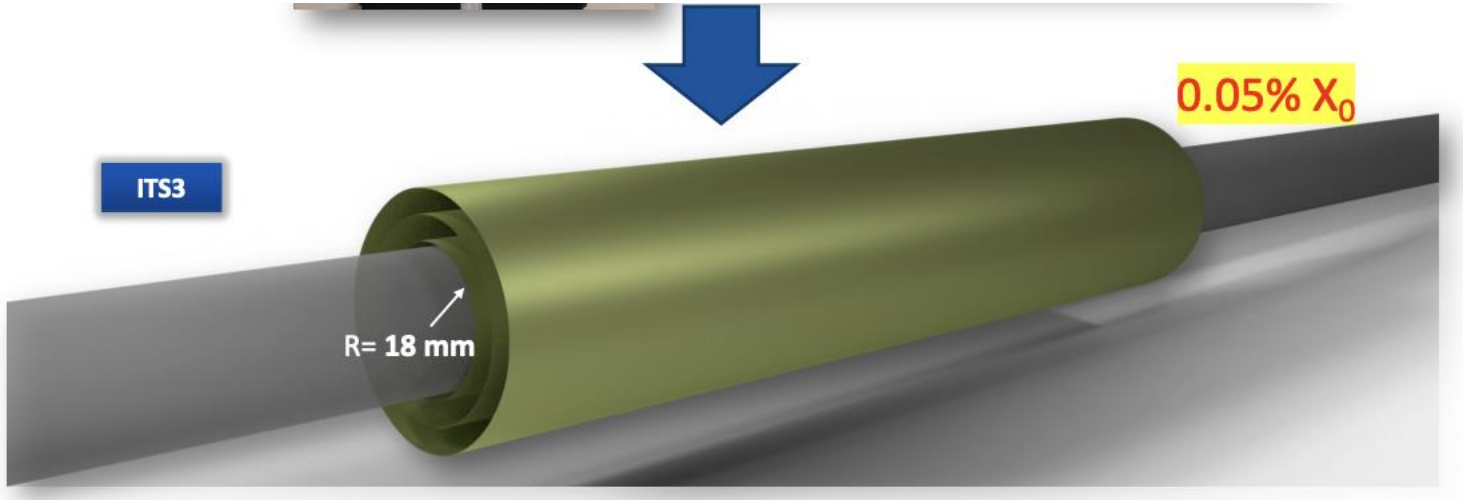
DRD3

Alice has installed a new vertex during Phase-1 upgrade planning for upgrade in Phase-3

- The main challenge for the physics achievement is the low material budget, only air cooling□ low power.
- Position resolution ~5 µm. radiation hardness modest ().



~12.5 Gpixels, 10 m² sensitive area
24120 **ALPIDE** Pixel Sensors (CMOS 180 nm)



ALICE ITS3 LoI CERN-LHCC-2019-018 / LHCC-I-034